Neighborhood Attributes and Cognitive Function in Older Adults

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Abstract

Neighborhood Attributes and Cognitive Function in Older Adults

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Background: Neighborhood environments are a potential modifiable factor for improving cognitive function among older adults by providing opportunities for physical activity and destinations for social interaction. Lifestyle factors enhance resilience to the development of brain pathology. However, the impact of neighborhoods on cognitive function and its mechanism among older adults is inconclusive.

Objectives: This dissertation consists of three studies. The aim of the first study was to determine the association of objective neighborhood attributes (land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, gradient of walkways, and areas covered by parks) with decline in cognitive function over a 2-year period among older adults. The aim of the second study was to examine the associations of perceived neighborhood attributes (residential density, land-use mix, transit ace\ss, bicycling infrastructure, recreation facilities, sidewalk coverage, crime safety, traffic safety, and physically active neighbors) with

cognitive function among older adults. The aim of the third study was to test a mediating role of walking on the association between objective walkability and cognitive function or perceived walkability and cognitive function among older adults.

Research Design: This dissertation employed a secondary data analysis method using the Adult Changes in Thought (ACT) study, a prospective cohort study. Data on neighborhood characteristics from 2016 King County Assessor, 2016 US Census TIGER/Line road, King County Geographic Information Systems Center, UW Urban Form Lab, and USGS digital elevation raster model (DEM) were combined with the ACT dataset. The first study was a longitudinal analysis in a sample of 1,302 older adults living in King County. Change in cognitive function was measured over 2 years by the Cognitive Ability Screening Instrument (CASI). Objective neighborhood attributes (land-use mix, residential density, intersection density, presence of trail, presence of sidewalk, gradient of walkways, and park area) were measured by geographic information systems (GIS). Multivariate linear regression models were fitted. The second study was a cross-sectional analysis in 821 adults aged 65 or older. Perceived neighborhood attributes were measured by the Physical Activity Neighborhood Environment Scale (PANE). The associations were tested using linear regression. The third study was a cross-sectional analysis in 799 older adults for the associations between objective walkability and cognitive function and in 680 older adults for the associations between perceived walkability and cognitive function. Walking was measured using an accelerometer. Associations were tested using linear regression. Indirect effects were tested using causal mediation analysis.

Results: The first study found that greater objective park area within an 800 m buffer was associated with positive change in cognitive function. However, the effect size was small. Other objective neighborhood attributes were not associated with cognitive function change. The

second study found that greater perceived access to public transit was associated with better cognitive function, and greater perceived sidewalk coverage was also related to better cognitive function. Perceived land use-mix and recreational facilities, crime, safety, safety from traffic, and neighbors physically active were associated with cognitive function in only unadjusted models. The third study revealed that walking had an indirect effect on the association between perceived walkability and cognitive function but not on the association between objective walkability and cognitive function.

Conclusions: Strategies targeting both environmental factors as well as individual behavioral factors should be considered to improve cognitive function in older adults. Improving the perception of neighborhood attributes alongside modifying physical infrastructure may positively impact cognitive function in older adults. Modifying neighborhood infrastructure may not be sufficient to improve perceived walkability. Educational and social support programs are required to improve perceived walkability. The improved perceived walkability may encourage older adults to be more physically active and the benefits of physical activity may improve cognitive function in older adults.

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Chapter 1. Introduction

More than 6 million people are estimated to have Alzheimer's Disease and Alzheimer's Disease Related Dementias (AD/ADRD) in the United States (US) (Alzheimer's Association [AA], 2021). The risk of developing AD/ADRD increases with age (Lucca et al., 2020). The number of people living with AD/ADRD is projected to rise rapidly as the number of people age 65 and older increases (AA, 2021). Total annual payments of health care and long-term care for individuals living with AD/ADRD are estimated at is $355 billion (AA, 2021). Loss of cognitive health, including cognitive decline and dementia, can detrimentally affect functional independence and quality of life (Hendrie et al., 2006; Petrovsky et al., 2018). In the absence of available pharmacologic treatments for stopping the progression of AD/ADRD, it is important to identify factors that prevent and delay cognitive decline (Ahmadzadeh et al., 2020; Clare et al., 2017; Frankish & Horton, 2017; Rocca et al., 2011).

Neighborhood environments have attracted attention as a potential factor for reducing and delaying decline in cognitive function (Besser et al., 2017; Wu et al., 2015). Social and physical neighborhood environments with qualities such as being traversable, compact, safe, and attractive may have benefits on cognitive function through promoting physical activity, social interactions, and cognitively stimulating activity (Forsyth, 2015; Lee & Waite, 2018; Wu et al., 2017). However, limited evidence is available for the role of neighborhood environments on cognitive function, particularly for older adults. Few studies have investigated the associations between objectively measured neighborhood attributes and cognitive function. Most of these studies used cross-sectional designs. Only a few studies employed a longitudinal design but even those had a small sample size and measured neighborhood attributes (i.e., street connectivity and integration) using geographic information systems (GIS) within a 800m buffer (Watts et al., 2015). Another longitudinal study measured neighborhood features (i.e., presence of community

center, public transit, and cross walks, discontinuous sidewalks, and public spaces in poor condition) by a neighborhood audit within census block group (Clarke et al., 2015) that may not be matched with areas where older adults actually spend their time for physical activity and social interactions in neighborhoods.

Furthermore, studies that have included subjective measures (i.e., questionnaires) for neighborhood environments often assume implicitly or explicitly that the perceived neighborhood environments capture the actual, physical neighborhood environments (Kamphuis et al., 2010). However, a few studies found low to moderate association between objective and perceived neighborhood attributes (Gebel et al., 2009; Michael et al., 2006). Older adults who reside in the same physical neighborhood may perceive their physical neighborhoods differently depending on their educational attainment, household income, social cohesion, affective state, and health condition (Gebel et al., 2009; Kamphuis et al., 2010). The varying levels of perceived neighborhood attributes may be differentially related to stress from neighborhoods and health behaviors such as physical activity and social engagement in their neighborhoods. The health behaviors may be associated with different harmful or beneficial impacts on cognitive function among older adults. Despite potential and independent impacts of perceived neighborhood on cognitive function, most studies have focused on objectively measured neighborhood attributes. Associations between cognitive function and perceived neighborhood attributes (i.e., residential density, connectivity, infrastructure, aesthetics, land-use mix, traffic safety, and crime safety) measured by adapted version of the Neighborhood Environment Walkability Scale (NEWS) were assessed among people aged 55 years and older in Singapore (Ng et al., 2018). However, the evidence on the perceived neighborhoods and cognitive function among adults aged 65 years and older in the US is limited.

Lastly, the mechanism of the association between neighborhood environments and cognitive function in older adults is not fully understood. Identifying the mediating factors between neighborhoods and cognitive function may be helpful to understand the role of neighborhood environments in relation to cognitive function as well as determine points to intervene or evaluate the effectiveness of the intervention. However, studies that examined potential mediators for the association between neighborhood attributes and cognitive function did not test the mediating effect using a formal causal mediation analysis (Clarke et al., 2012; Koohsari et al., 2019; Ng et al., 2018).

This dissertation is a secondary data analysis. Data were obtained from the Adult Changes in Thought (ACT) study and data on objectively measured neighborhood were combined with the ACT study data. The dissertation consists of three studies. Throughout the three studies, cognitive function was assessed by the Cognitive Ability Screening Instrument (CASI). The aim of the first study was to determine the association of objective neighborhood attributes (land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, gradient of walkways, and areas covered by parks) with decline in cognitive function over a 2-year period among older adults aged 65 years and older. The neighborhood attributes were assessed within 400 m, 800 m, and 1,600 m Euclidean buffers around the location of residence by GIS. The aim of the second study was to examine the associations of perceived neighborhood attributes (residential density, land-use mix, transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, crime safety, traffic safety, and physically active neighbors) with cognitive function in older adults. The objective and perceived neighborhood attributes were included in these studies because those attributes may have potential impacts on cognitive function in older adults through modifying physical activity,

social activity, and cognitively stimulating activity. The third study tested a mediating role of walking on the association between objective neighborhood and cognitive function as well as perceived neighborhood and cognitive function.

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Chapter 2. Neighborhood Environments and Cognitive Function in Older Adults

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Abstract

Background: Neighborhoods can provide older adults opportunities for physical activity and destinations for social interaction. Lifestyle factors have been found to enhance resilience to the development of brain pathology. However, the impact of neighborhoods on cognitive function among older adults is inconclusive. This study examined the association of neighborhood attributes with change in cognitive function over 2 years among older adults.

Methods: This is a secondary analysis using longitudinal data. Data were obtained from multiple sources, including the Adult Changes in Thought (ACT) study, the University of Washington's Urban Form Lab, King County Assessor, and King County Geographic Information Systems Center. Individual-level and neighborhood-level data were linked based on spatial location information. Change in cognitive function was measured over 2 years by the Cognitive Ability Screening Instrument (CASI). Land-use mix, residential density, intersection density, presence of trail, presence of sidewalk, gradient of walkways, and park area were objectively measured by geographic information system (GIS). Multivariate linear regression models were fitted.

Results: Greater park area within an 800 m buffer was associated with positive change in cognitive function. Other objective neighborhood attributes were not associated with cognitive function change.

Conclusions: The findings suggest that accessibility of parks in a neighborhood may have benefits for cognitive function among older adults. However, further studies are required to determine the association between park area and cognitive function change in older adults. Strategies targeting both physical environmental factors as well as individual behavioral factors should be considered to improve cognitive function in older adults.

Introduction

Loss of cognitive function limits individuals in maintaining an ongoing sense of purpose, social interactions, the ability to live independently, greater success in recovering from illness or injury, and the capacity to cope with functional deficits (1). Of the 58 million adults who are age 65 and older in the United States (US) as of 2021, 6.2 million people are estimated to have Alzheimer's Disease and Alzheimer's Disease Related Dementias (AD/ADRD) (2). The estimated annual cost of health care and long-term care for people with AD/ADRD in 2021 is $355 billion (2). Furthermore, in 2021, the economic value of informal care provided by almost 11 million Americans is estimated at $256.7 billion (2). Given the significant physical, social, and economic costs associated with loss of cognitive function in older adults, identifying ways to reduce risk and slow the progress of decline in cognitive function is essential.

The varying levels and rates of cognitive function decline in individuals with the same degree of brain pathology may be attributed to differences in cognitive reserve, a concept which has been proposed to account for individual variations in clinical symptoms (3). Cognitive reserve is the ability to optimize or maximize performance through more efficient use of brain networks or the recruitment of alternate networks (3). An individual with greater cognitive reserve capacity may show a delay in the expression of clinical symptoms and a slower progression of dementia (3). Lifestyle factors have been found to enhance cognitive reserve through improving resilience to brain pathology (4).

Individual lifestyle factors, such as physical activity, a healthy diet, cognitive activity, and social engagement, are known to reduce the risk of cognitive function decline and the development of dementia (1, 5). Recently, there has been a growing interest in neighborhoods as one source of modifiable factors for cognitive function improvement through promoting healthy

lifestyle. Neighborhood attributes promoting physical, social, and cognitive activities include greater land-use mix (i.e., co-location of places for living, commerce, and obtaining services), greater residential density, interconnected streets, sidewalk coverage and trails, minimal gradient of walkways, and parks that create walkways that are traversable, compact (i.e., a short distance to destinations), safe, and aesthetically attractive (6-8).

Few studies have examined the association of objectively measured neighborhood attributes with cognitive function. Diverse neighborhood attributes were assessed by different definitions and methods across studies and the associations of each neighborhood attribute with cognitive function were tested (7, 9-12). Presence of recreational centers were significantly associated with cognitive function in two studies (7, 10) but not in another study (12). Street connectivity was significantly related to cognitive function (9, 11). Most of these studies employed a cross-sectional study design and only a few were conducted in the US (7, 9, 12). A longitudinal study with a 2-year follow-up obtained data from a convenience sample of 64 older adults living in Kansas City, Missouri (11). This longitudinal study had small and not representative sample. Another longitudinal study over an 18-year study period defined a neighborhood as a census block group and assessed neighborhood attributes for each neighborhood unit using neighborhood audits (10). This longitudinal study defined neighborhoods by an administrative areal unit (census block group) which may not represent home neighborhoods. Given the lack of longitudinal studies with population-based random samples and evidence on which neighborhood attributes are essential to cognitive health in older adults, it would be valuable to conduct a longitudinal study to examine the associations between neighborhood attributes and cognitive function.

The aim of this study was to determine the association of neighborhood attributes (i.e., land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, gradient of walkways, and areas covered by parks) with change in cognitive function over a 2-year period among older adults. We hypothesized that greater land-use mix, residential density, intersection density and park areas, the presence of trails and sidewalks, and minimal gradient of walkways were associated with better cognitive function.

Methods

Design and Participants

This study used a secondary longitudinal analysis to examine associations between neighborhood attributes and change in cognitive function. Data were obtained from the Adult Changes in Thought (ACT) study, a prospective cohort study focusing on dementia and aging. The detailed study design of ACT study was described elsewhere (13). Briefly, a simple random sample was drawn from members of Kaiser Permanente Washington (KPWA) residing in King County, Washington who were community-living older adults aged 65 years or older. Potentially eligible participants were screened for dementia; those with an existing diagnosis of dementia were excluded at enrollment. Of 5,422 eligible potential subjects, 2,581 participants were enrolled in the ACT cohort from 1994 to 1996. The proportion of refusal was higher among women and the oldest age groups. An expanded cohort of 881 individuals was enrolled from 2000 to 2003 (14) and continuous enrollments were initiated in 2004 to compensate for diminishing cohort size over time (15). Participants were followed biennially until dropout, death, or dementia diagnosis.

In this sub-study, participants who completed two research visits between 2016 and 2019 (to calculate change in cognitive function over 2 years), resided in King County, and had

geocoded addresses were eligible. Individuals who lived in long-term care settings during the study period were excluded. A total of 1,486 possible participants completed two research visits from 2016 to 2019. However, 128 observations were excluded due to either living outside of King County (n = 109) or living in long-term care settings (n = 19) between 2016 and 2019. Thus, a total of 1,358 participants were eligible for this study. All participants had no notable dementia symptoms that could be identified using a screening tool (Cognitive Abilities Screening Instrument) during the first research visit of the study period. If participants moved during the study period, the address where participants lived for a longer time was selected. For addresses with equal residential duration, the address when the outcome was measured was chosen. The Institutional Review Board of the University of Washington approved this study.

Measures

Cognitive function

Cognitive function was measured with the Cognitive Ability Screening Instrument (CASI) (16). The CASI consists of nine domains: attention, concentration, orientation, short-term memory, long-term memory, language abilities, visual construction, list-generating fluency, and abstraction and judgment. Total CASI score can be utilized to identify possible presence of dementia (16). Total score contains more information than domain specific scores, so that total score was chosen in this study. The total score ranges from 0 to 100, with a higher score indicating better cognitive function (16).

Neighborhoods

To protect individual subjects' identities, residential locations were provided at the census block level, rather than as the actual location of residence. The home neighborhood was defined as an 800 m Euclidean buffer around the census block centroid, a proxy for actual

location of residence; this distance corresponds to roughly 10 minutes of walking. Additionally, the median walking trip distance was found to be 729 m in older adults living in a medium-sized city (17). In addition to the 800 m buffer, 400 m and 1,600 m buffers were also explored. The areas covered by water were removed from the buffers.

The size of census blocks varies, but census blocks correspond to a typical city block in urban areas (18). The majority of participants lived in urban areas where the 800 m buffer was a much larger area than a city block (area of 800 m buffer = 2,010,619 m^2). The mean area of the census blocks where participants lived was 50,371 m^2. The 800 m buffer unquestionably covered the actual location of residence and substantially captured the surrounding areas of the actual address (Figure 1).

Neighborhood attributes

Exposure variables included were land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, gradient of walkways, and park area. Geographic information system (GIS) was used for all the spatial data processing. *Land-use mix* was measured using the equation proposed to describe the evenness of the distribution of areas in square meter of residential, commercial, and office land usages within a buffer area in square meter (8, 19) based on parcel data from 2016 King County Assessor's data. The highest value was assigned to the most mixed-use buffer area. *Residential density* was calculated as the number of housing units within a buffer divided by the buffer area (with water areas excluded), also from 2016 King County Assessor's data. *Intersection density* was calculated using the number of intersections (from 2016 US Census TIGER/Line road data) that were at least 3-way within a buffer area. Higher residential density and intersection density values indicate greater density of residential units and intersections within a buffer area (count/m^2). Residential density

and intersection density data were converted from vector format using the selected radii to SmartMaps, a spatial data format created for efficient data extraction for neighborhood-level variables at any point location within the study area (20).

Access to trails was measured as the total length of trails in meter within a buffer area in square meter using the 2019 data from the King County Geographic Information Systems (KCGIS) center. The data on trails contained any trails in the King County system, but city and private trails may not be included in the data set. Access to trails was dichotomized according to whether residents had access to a trail in their neighborhood or not. *Sidewalk coverage* was defined by a ratio of the length of streets with sidewalks on either the left or right side divided by the total length of streets within a buffer area. The proportion of presence of sidewalk was calculated using data collected from 2011 to 2012 by the University of Washington's Urban Form Lab. The proportion of presence of sidewalk was recalculated to a percentage by multiplying by 100. The sidewalk coverage score of 100 means that sidewalks were present on all streets within a buffer. *Gradient of walkways* was measured as the mean slope in percent of all areas within a buffer area where 0% indicates flat and 100% indicates 45 degrees, based on USGS digital elevation raster model (DEM) data. *Park area* was assessed by the total area of parks within a buffer area. Park area was measured in hectare. Park data were obtained from multiple jurisdictions in King County and combined to a single data set by the Urban Form Lab in 2008 and converted to SmartMap format (20).

Individual-level covariates

Potential confounders were age (65-74 years, 75-84 years, ≥ 85 years), sex at birth (female, male), race/ethnicity (non-White race or Hispanic ethnicity, non-Hispanic White), and education (< 12 years, 12-15 years, > 15 years). All potential confounders were measured during

the first visit of the study period. Duration of residence at the addresses used in this study was calculated and categorized into four levels (1-5 years, 6-10 years, 11-20 years, and ≥ 21 years).

Neighborhood-level covariate

A potential confounder at the neighborhood-level was neighborhood socioeconomic status. Neighborhood socioeconomic status was measured using the Area Deprivation Index (ADI) (21). The ADI includes 17 indicators from four domains: income, employment, education, and housing quality (22, 23) and was calculated using 2015 American Community Survey (ACS) 5-year estimates. The ADI score was available at the census block group level, and a weighted ADI score was recalculated for each buffer by the proportion of areas within a buffer using GIS ADI scores from national percentile rankings range between 1 (least disadvantaged) and 100 (most disadvantaged).

Statistical Analysis

The association between a neighborhood's environmental characteristics and a resident's cognitive function was assessed using multivariate linear regression. Each exposure, measured at 400 m, 800 m (primary buffer size), 1,600 m buffers, was assessed in a separate model to examine the independent association between neighborhood characteristics and cognitive function. Multiple sizes of buffers were utilized because the inference could be different depending on the size, shape and zone of areal units (24). Two observations were available at each individual. There was little variation in CASI total scores across individuals. The difference in scores from the CASI total score at the second visit and the CASI total score at the first visit was calculated and included in the regression model as an outcome variable. All regression models were adjusted for age, sex at birth, race/ethnicity, education, and neighborhood socioeconomic status. The data did not contain any evidence of potential geographic clusters;

hence no random effects were included to represent clusters of study participants. Census tract data were available to explore the potential hierarchical structure of the data. Participants' home locations were contained within 223 census tracts, and half of these included only one to four participants. Additionally, the average of the cognitive function scores by census tracts did not show substantial variance, with the 25th and 75th percentiles being 93.0 and 96.3, respectively, within a possible range from 0 to 100. Sensitivity analysis was performed within a subgroup of participants who had lived at the address more than 10 years. All statistical analyses were performed using R version 3.6.2 (25), and GIS analysis was conducted using Esri ArcGIS Pro (version 2.4) (26). Processing of vector data to SmartMaps was performed using R 3.6.0 with the sf, raster, and velox packages, and PostgreSQL 11.6 with the PostGIS 2.5 spatial extension.

Results

Sample Characteristics

Of 1,358 eligible participants, 56 observations (4%) had missing values on the following variables: CASI score (n = 26, 1.9%), variables obtained from SmartMaps (n = 20, 1.5%), sidewalk coverage (n = 3, 0.2%), and race/ethnicity (n = 7, 0.5%). After excluding missing data, 1,302 participants were included in analyses.

Characteristics of participants and their neighborhoods are presented in Table 1. The mean age was 77.8 (SD = 7.1) years. More than a half of the participants were female (n = 760, 58.4%). The majority of participants were non-Hispanic White (n = 1,139, 87.5%) and had completed some level of post-college education (n = 969, 74.4%). The range of the length of residence was from 1 to 53 years with about half of the participants having lived at the address more than 20 years (n = 614, 47.2%). The ADI score was, on average, 14.8 (SD = 10.3) and 75% of participants were living in a neighborhood within the top 20th percentile according to the

national ADI score ranking (1st percentile meaning least advantaged and 100th percentile meaning most disadvantaged). Cognitive function scores declined by 1.2 points on average (*SD* = 4.2) over the 2-year study period.

Neighborhoods Attributes and Cognitive Function

Neighborhood attributes, including land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, gradient of walkways, and park area were separately examined with cognitive function change over 2 years (Table 2). At the 800 m buffer, park area was associated with better cognitive function change over 2 years ($p = 0.04$). One unit (hectare) difference in park area within a neighborhood was associated with 0.016 points greater change in cognitive function (i.e., a 0.016 point rises in cognitive function test over 2 years on average) after controlling for age, sex at birth, race/ethnicity, education, and neighborhood socioeconomic status (95% confidence interval [CI]: 0.000, 0.032). The significant association between park area and cognitive function was not observed in the analyses using 400 m and 1,600 m buffers. Other neighborhood attributes were not associated with cognitive function change.

Sensitivity analysis was performed in the subgroup of participants who had lived at their address more than 10 years *(n* = 993, Table 3). The sensitivity analysis showed generally consistent results with primary analyses.

Discussion

In this study, we examined the associations between neighborhood characteristics and cognitive function change over a 2-year period in older adults. This study objectively assessed neighborhood environmental features in three differently sized buffers. As such, the study allowed us to check the robustness of the findings and to determine an appropriate operational definition of neighborhoods for older adults. Based on a previous study that reported 729 m as

median walking trip distance in older adults (17), we hypothesized that an 800 m buffer size was likely better at measuring the neighborhood for older adults. We found statistically significant association between greater park area within 800m buffers and better cognitive function change among older adults. This finding supports our hypothesis that greater park area is associated with better cognitive function. Parks can offer a natural environment and a place for social interaction and physical activity, which are all related to better cognitive function (27-29). However, the p-value for the association between park area and cognitive function change was only marginally significant. The effect size was small and the change in cognitive function may be not clinically meaningful. Additionally, the association between park area and cognitive function change was not observed at the 400 m and 1,600 m buffer sizes. Thus, the significant association should be interpreted with caution.

Published studies of the association between park area and cognitive function have reported findings that are inconsistent with the findings of this study (7, 30). A cross-sectional study analyzed data from 949 people aged 50 and over living in Chicago, Illinois (7). It found that park area within a census tract was not associated with cognitive function as measured by a modified version of the Telephone Instrument for Cognitive Status. It is possible that our finding does not align with the finding from this cross-sectional study because of the different ways that neighborhoods were defined in each (circular buffer vs. census tract) and different inclusion criteria of age (65 years and over vs. 50 years and over). The modifiable areal unit problem (MAUP) refers to a form of bias that statistical findings are significantly influenced by the unit of spatial area (31). Therefore, the areal units of the neighborhoods as defined by each study likely played a significant role in the inconsistency of the findings. Furthermore, the spatial composition and configuration of parks may differ between the two sites.

A retrospective cohort study conducted in Edinburgh and the Lothians in Scotland used data from the Lothian Birth Cohort 1936 (30). The study demonstrated that greater park area within a 1,500 m buffer surrounding the participant's home during childhood was associated with positive cognitive function change from age 70 to 76 years measured with the Moray House Test No. 12, conditional on early adulthood park area (30). This longitudinal study did not show a relationship between park area in later adulthood and cognitive function change from age 70 to 76 (30). Both our study, using a 1,600 m buffer, and this longitudinal study, using a 1,500 m buffer, did not find a significant association between later adulthood park accessibility measured by park area and cognitive function change. The 1,600 m buffer could include parks so far away from one's home that older adults may not walk to or use them. The potential mismatch between actual use of parks and objectively measured park area may contribute to why the study did not find a significant association between park area and cognitive function in older adults. Given the limited existing literature, it is still inconclusive if park area can support cognitive function in older adults. Our finding adds some evidence of the association between park area and cognitive function in older adults. Further research is required to determine the appropriate buffer size around the residences of older adults and the effects of park availability on cognitive function. Additionally, assessing whether proximal parks are actually used may have an independent effect from the mere existence of proximal parks.

Our study did not find associations of other neighborhood attributes, including land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, and gradient of walkways with cognitive function change over 2 years. We included these neighborhood attributes because they can offer opportunities for social, physical, and cognitive activities (32, 33). Social engagement can contribute to improved psychological well-being and physical

activity, which are known to be protective factors for cognitive health (5, 34, 35). Physical activity can induce positive effects on psychological well-being as well as neuroplasticity and compensatory mechanisms against neurodegeneration related to aging that affects brain structure and cognitive function (36). Given the lack of literature, further studies are needed to determine the association between objectively measured neighborhood attributes and cognitive function in older adults. It is also important to examine the role of perceived neighborhood attributes on cognitive health along with objective neighborhood attributes to determine which neighborhood characteristics are critical for promoting cognitive function in older adults. Furthermore, mediation analysis is also required to examine which pathways, from neighborhood factors to health behaviors and from health behaviors to cognitive function, are broken to further understand the impact of neighborhood environments on cognitive function in older adults.

This study had several limitations. First, the 2-year follow-up time was relatively short for observing substantial changes in cognitive function or trends of the rate of cognitive decline given the long-term preclinical stage of the initiation of pathophysiology of dementia prior to clinical manifestation of symptoms (37). The little variability in outcome can limit the ability to find the significant association. However, the primary interest of this study was the association between neighborhood attributes and change in cognitive function rather than levels of cognitive function. Additionally, there was little variation in total cognitive function as well. Thus, the difference in cognitive function scores were used as outcome. Future studies need to examine the relationship of neighborhood attributes to the rate of cognitive decline over a longer period. Second, even though we found statistically significant association between park area and change in cognitive function, but the effect size was small. This could be because participants are mostly healthy, educated, and lived neighborhood with moderate to high neighborhood socioeconomic

status. This may lead to little variability in both neighborhood attributes and cognitive function values and resulted in the small effect size. Future studies should sample participants from diverse neighborhoods with varying levels of neighborhood attributes. Third, any home-centered neighborhood buffers may not accurately represent the activity space where older adults actually spend their time and accumulate exposure to environmental features (38). If the definition of neighborhoods is invalid, neighborhood features measured within a buffer can be overestimated or underestimated and the association can be distorted in a positive or negative direction. There is no standardized definition of neighborhoods for older adults, so this study utilized 800 m buffer as a primary buffer size and added 400 m and 1,600 m buffers to compare the findings across buffer sizes. Further studies comparing different buffer shapes (e.g., network-based rather than Euclidean) and sizes are needed to further understand the definition of the neighborhoods where older adults actually spend their time. A valid measure of services and places used by an individual based on accurate definition of neighborhoods (i.e., size, shape, location) would be helpful to draw more reliable findings and such findings could be used to inform the development of structural interventions. Lastly, the possibility of residential self-selection bias remains. Selection of neighborhoods can be affected by a variety of factors, such as affordability, convenience, health status, and preference for physical activity (39, 40). The association between neighborhood environments and health outcomes can be due to the effects of neighborhoods on health, the effects of personal characteristics related to neighborhood selection, or both (40). We controlled for age, race/ethnicity, education, and neighborhood socioeconomic status, each of which can be associated with neighborhood selection, but the residential self-selection bias was not fully adjusted. Further longitudinal studies examining the effects of changes in exposures on

changes in outcomes are required to mitigate the effects of self-selection of neighborhoods on health outcomes (40).

Conclusion

The current study suggests the potential association of park area with cognitive function change in older adults. The findings are relevant to the National Institute on Aging's strategic directions for research to promote physical activity and social engagement by conducting studies of the built environment (41). Comprehensive strategies that focus on a variety of both environmental factors as well as individual factors can be more effective to improve cognitive health in older adults than those that focus only on one aspect. Findings from this study can inform policy makers, urban design planners, practitioners, and researchers of innovative strategies to improve cognitive health in older adults through modifying neighborhood environments.

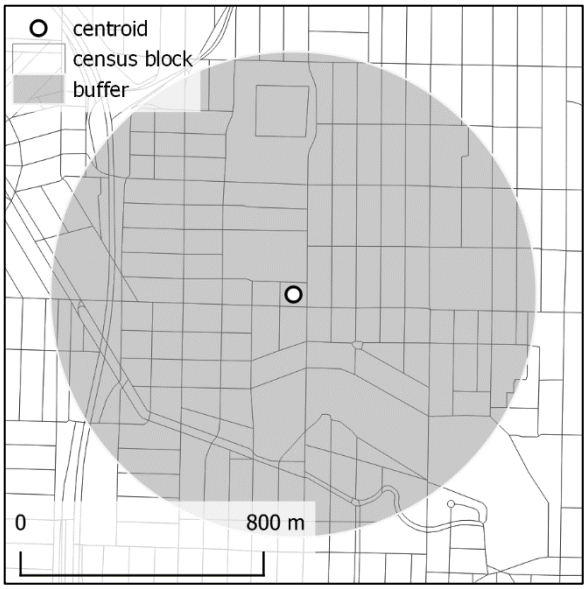

Figure 2.1 Example of 800 m buffer around a census block centroid

Table 2.1 Individual-level demographic characteristics and neighborhood-level characteristics of participants at baseline (N = 1,302)

Characteristics	***n* (%)**
Individual-level characteristic	
Age group	
65-74 year	498 (38.2)
75-84 year	562 (43.2)
≥ 85 year	242 (18.6)
Sex at birth	
Female	760 (58.4)
Male	542 (41.6)
Race/ethnicity	
Hispanic ethnicity or non-White race	163 (12.5)
Non-Hispanic White	1139 (87.5)
Education	
< 12 year	20 (1.5)
12-15 year	969 (74.4)
> 15 year	313 (24.0)
Length of residence	
1-5 year	121 (9.3)
6-10 year	188 (14.4)
11-20 year	379 (29.1)
≥ 21 year	614 (47.2)
Cognitive Abilities Screening Instrument (CASI), M (SD)	95.6 (3.6)
Change in CASI over 2-year, M (SD)	-1.2 (4.2)
Neighborhood-level characteristic	
Trail access	
Yes	702 (53.9)
No	600 (46.1)
Land-use mix, M (SD)	0.4 (0.3)
Residential density (count/m^2), M (SD)	18.5 (17.0)
Intersection density (count/m^2), M (SD)	0.7 (0.3)
Sidewalk coverage (%), M (SD)	58.7 (26.0)
Park area (hectare), M (SD)	12.6 (14.5)
Gradient of walkways (%), M (SD)	36.4 (12.7)
Area Deprivation Index (%), M (SD)	14.8 (10.3)

All neighborhood-level characteristics were measured within 800m buffers. For gradient of walkways, 0% indicates flat and 100% indicates 45 degrees. For Area Deprivation Index, 1% refers to a neighborhood with least disadvantaged and 100% refers to a neighborhood with most disadvantaged.

Table 2.2 Associations of neighborhood attributes by buffer size (m) with cognitive function change over 2 years (N = 1,302)

	Coefficient (95% CI)	***p*-value**
Land-use mix		
400	0.458 (-0.323, 1.239)	0.250
800	0.465 (-0.379, 1.308)	0.280
1600	0.181 (-0.813, 1.175)	0.721
Residential density (count/m^2)		
400	0.005 (-0.004, 0.015)	0.283
800	0.002 (-0.011, 0.015)	0.767
1600	0.001 (-0.014, 0.017)	0.842
Intersection density (count/m^2)		
400	-0.134 (-0.866, 0.599)	0.720
800	-0.127 (-0.975, 0.722)	0.770
1600	-0.037 (-1.024, 0.949)	0.941
Trail access (yes vs. no: reference)		
400	0.196 (-0.301, 0.693)	0.439
800	0.034 (-0.412, 0.480)	0.881
1600	-0.100 (-0.693, 0.493)	0.741
Sidewalk coverage (%)		
400	0.000 (-0.008, 0.008)	0.986
800	0.003 (-0.006, 0.012)	0.573
1600	0.002 (-0.008, 0.013)	0.645
Gradient of walkways (%)		
400	0.013 (-0.002, 0.027)	0.080
800	0.013 (-0.006, 0.031)	0.188
1600	0.011 (-0.016, 0.038)	0.429
Park area (hectare)		
400	0.043 (-0.009, 0.095)	0.107
800	0.016 (0.000, 0.032)	0.044
1600	0.003 (-0.001, 0.009)	0.274

Each exposure was separately tested using a linear regression model and adjusted for age, sex at birth, education, race/ethnicity, and neighborhood socioeconomic status. For land use mix, larger value indicates greater mixed use of land. For gradient of walkways, 0% indicates flat and 100% indicates 45 degrees.

Table 2.3 Sensitivity Analysis of associations of neighborhood attributes by buffer size (m) with cognitive function change over 2 years (N = 993)

	Coefficient (95% CI)	***p*-value**
Land-use mix		
400	-0.034 (-1.018, 0.951)	0.947
800	0.122 (-0.913, 1.157)	0.817
1600	0.009 (-1.193, 1.212)	0.988
Residential density (count/m^2)		
400	0.000 (-0.012, 0.013)	0.964
800	-0.007 (-0.024, 0.009)	0.393
1600	-0.014 (-0.034, 0.006)	0.168
Intersection density (count/m^2)		
400	-0.495 (-1.349, 0.360)	0.256
800	-0.926 (-1.954, 0.102)	0.077
1600	-1.003 (-2.199, 0.193)	0.100
Trail access (yes vs. no: reference)		
400	0.139 (-0.446, 0.723)	0.642
800	0.162 (-0.350, 0.675)	0.534
1600	-0.150 (-0.821, 0.522)	0.662
Sidewalk coverage (%)		
400	-0.002 (-0.012, 0.007)	0.600
800	-0.003 (-0.013, 0.007)	0.592
1600	-0.005 (-0.017, 0.007)	0.389
Slope (%)		
400	0.009 (-0.008, 0.026)	0.284
800	0.009 (-0.013, 0.031)	0.416
1600	0.017 (-0.015, 0.049)	0.304
Park area (hectare)		
400	0.042 (-0.019, 0.104)	0.178
800	0.018 (-0.001, 0.036)	0.063
1600	0.006 (-0.002, 0.013)	0.125

Sensitivity analysis was performed in a subgroup of participants who have lived the address more than 10 years. Each exposure was separately tested using a linear regression model and adjusted for age, sex at birth, education, race/ethnicity, and neighborhood socioeconomic status. For land use mix, larger value indicates greater mixed use of land. For gradient of walkways, 0% indicates flat and 100% indicates 45 degrees.

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Chapter 3. Association of Perceived Neighborhood Environments with Cognitive Function in Older Adults

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Abstract

Background: Neighborhood environments are considered a potential modifiable factor for improving cognitive health. Individuals who reside in similar surroundings may differ in their perceptions of physical neighborhood environments. Perceived neighborhoods can have different impacts on healthy behaviors and outcomes; however, there has been scant research on perceived neighborhood attributes. Consequently, this study examined the associations between perceived neighborhood attributes and cognitive function in older adults.

Methods: This cross-sectional study analyzed 821 adults aged 65 or older from the Adult Changes in Thought study. Perceived neighborhood attributes were measured by the Physical Activity Neighborhood Environment Scale. Cognitive function was assessed using the Cognitive Ability Screening Instrument (CASI), and the associations were tested using linear regression.

Results: Greater perceived access to public transit was associated with better cognitive function, and greater perceived sidewalk coverage was related to better cognitive function after controlling for individual-level sociodemographic factors. Perceived land use-mix and recreational facilities, crime, safety, safety from traffic, and neighbors physically active were associated with cognitive function in only unadjusted models.

Conclusions: Improving the perception of neighborhood attributes alongside modifying physical infrastructure may positively impact cognitive function in older adults. Future studies need to investigate potential mediators to further understand the associations between perceived neighborhoods and cognitive function and examine factors to better influence the perception of neighborhood environments. This research provides a foundation for developing strategies to improve perceptions of neighborhood environments in older adults.

Introduction

The number of individuals with dementia is growing (Frankish & Horton, 2017). As of 2021, an estimated 6.2 million adults aged 65 and older are living with Alzheimer's Disease and Alzheimer's Disease Related Dementias (AD/ADRD) in the United States (US) (Alzheimer's Association [AA], 2021). It is the fifth leading cause of death among older adults in the US (AA, 2020). With no currently available treatments for AD/ADRD, efforts to identify modifiable factors which may delay the onset or progression of AD/ADRD have increased over the years (Ahmadzadeh et al., 2020; Clare et al., 2017; Frankish & Horton, 2017; Rocca et al., 2011). Neighborhood environments are considered a modifiable factor for reducing the risk of decline in cognitive function (Besser et al., 2017; Wu et al., 2015). Social and physical neighborhood environments with qualities of being traversable, compact, safe, and attractive can contribute to improving cognitive function, by promoting physical activity, social connections, and cognitive activity (Forsyth, 2015; Lee & Waite, 2018; Wu et al., 2017).

The ecological model of aging describes the relationship between individuals and their physical environments, with an emphasis on the role of individual perception of physical environments (Lawton & Nahemow, 1973; Lawton, 1982; Lawton, 1989). Individual behaviors are manifested through their interactions with the environment (Lawton, 1989). Individuals may appraise physical environment differently, depending on characteristics such as competence (e.g., health, physical function, and cognition) and personal resources (Lawton, 1982); behaviors may also vary across people even when they live in the same physical environment (Lawton 1989). The ecological model of aging framework describes perceived environments (perception to physical environments) and objective environments as distinct concepts (Lawton, 1982; Lawton, 1989). Studies have empirically examined the relationship between objective and

perceived neighborhood environments and shown low to moderate agreement between the objective and perceived neighborhood environments (Gebel et al., 2009; Michael et al., 2006). The research findings suggested that these environments may have different roles in promoting health.

Even though individuals reside in the same physical neighborhood, their health behaviors such as physical activity, social engagements, and stress from the neighborhood may be affected by how they perceive and interact with their physical neighborhood. The variations in health behaviors or stress across individuals may partially account for varying levels of cognitive function among those individuals. Despite the importance of perceived environments, there has been scant research to understand the relationship between perceived neighborhood environments and cognitive function among older adults compared to the association between objective neighborhood environments and cognitive function among older adults. This study examined the associations of perceived neighborhood attributes (residential density, land-use mix, transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and neighbors physically active) with cognitive function in older adults.

Methods

Design and Participants

This is a cross-sectional secondary analysis. We extracted data from the Adult Changes in Thought (ACT) study for the years 2016 to 2019. The ACT study is an ongoing prospective cohort study of older adults; it investigates the development of dementia and related risk factors (Kukull et al., 2002). A simple random sample was drawn from the Kaiser Permanente Washington members who were aged 65 years and older, did not have dementia, and resided in

King County, Washington, from 1994 to 1996. Continuous enrollment began in 2004 to replace dropouts and deaths (Mez et al., 2017). Cohort members were interviewed biennially and participants who were newly diagnosed with dementia were dropped from the cohort.

The Adult Changes in Thought Activity Monitor (ACT-AM) study is a sub-study of the ACT study. The ACT-AM study began in 2016, with the aim to better capture sedentary and active behavior patterns in older adults, using a monitoring device (Actigraph wGT3X+ and activPAL micro) (Rosenberg et al., 2020). Individuals who were bound to a wheelchair, receiving hospice care, diagnosed with a critical illness, having memory problems, or residing in a nursing home were excluded from the ACT-AM study. Perceived neighborhood was measured by the survey among ACT-AM study participants as well as ACT participants who did not consent to the ACT-AM study but agreed to answer the perceived neighborhood measure.

Participants who completed the perceived neighborhood measure and lived in King County were included in these analyses. There were 1,358 participants who also completed research visits between 2016 and 2019. Of them, there were 501 cases with missing values, which included at least one item of the perceived neighborhood survey (residential density, land-use mix, transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and neighbors physically active). Of the remaining 857 observations, 36 cases with missing values in race/ethnicity and cognitive function measure were excluded resulting in an analytic sample size of 821 individuals who tended to be younger, male, healthier, and more educated compared to the entire ACT cohort members.

Measures

Perceived neighborhood environment

Perceived neighborhood attributes (residential density, land-use mix, transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and neighbors physically active) were measured using a modified form of the Physical Activity Neighborhood Environment Scale (PANES) (Sallis et al., 2010). The PANES was designed to assess perceptions of social and built environment attributes among adults. In this questionnaire, a neighborhood was defined as the area surrounding a home that is within 10 to 15 minutes of walking distance. The original scale consists of 17 items which cover multiple constructs. Each item can be used separately as an independent construct, or they can be combined as an index. Perceived residential density was measured using an item assessing the main type of housing in neighborhood. Detached single-family housing was coded to low residential density, while other types of housing such as condos, townhouses, or apartments were categorized to high residential density. Perceived land-use mix was measured using two separate items. One item measures the variety of destinations such as shops, stores, markets, and other services present in a neighborhood (i.e., diversity of destinations); the second item measures the number of destinations within easy walking distance from home (i.e., access to destinations). Perceived transit access was measured by asking about the presence of a transit stop within a neighborhood. Perceived bicycling infrastructure was assessed by examining if there are facilities supporting bicycle use, such as special lanes, separate paths, or trails in a neighborhood. Perceived recreation facilities referred to identification of free or low cost recreation facilities, such as parks and recreation centers. Perceived sidewalk coverage was measured by asking if there are sidewalks on most of the streets in a neighborhood. The participants were also asked about perceived safety from crime (feeling unsafe—related to crime rate in a neighborhood—to go for walks at night), safety from traffic (experiencing difficulty or unpleasantness while

walking in a neighborhood due to traffic), and neighbors physically active (seeing many people being physically active in a neighborhood). Response options for all items other than residential density are based on a 4-point scale, ranging from 1 (strongly disagree) to 4 (strongly agree). Safety from crime and safety from traffic were reversely coded. A higher score indicates more favorable perceived neighborhood attributes. The response options can be used as either a numeric score or a dichotomized response. The numeric item scores were chosen for this study not to lose information by categorizing the values. The perceived neighborhood attributes were collected between 2016 and 2019.

Cognitive function

Cognitive function was assessed by the Cognitive Ability Screening Instrument (CASI) (Teng et al., 1994). The CASI consists of nine domains: attention, concentration, orientation, short-term memory, long-term memory, language abilities, visual construction, list-generating fluency, and abstraction and judgment. Total CASI score can be used to screen for dementia and CASI domain scores can be applied to describe profiles of cognitive impairment (Teng et al., 1994). The association between of neighborhood attributes with the total score rather than domain specific scores can provide better information on identifying protective neighborhood attributes for cognitive function. The total score ranges from 0 to 100; a higher score indicates higher cognitive function. The CASI score data were collected between 2018 and 2019, except for two cases (collected in 2017).

Covariates

Individual factors of age, sex at birth (female, male), race/ethnicity, and educational attainment were collected. Age was categorized into three levels (65–74 years, 75–84 years, ≥ 85 years) and race/ethnicity was coded into non-Hispanic White versus Hispanic ethnicity or non-

White race. Education was categorized into three levels (< 12 years, 12–15 years, > 15 years). Age data were collected at the first visit between 2016 and 2018.

Statistical Analysis

Descriptive statistics were calculated for demographic characteristics, exposures, and outcome. The associations between perceived neighborhood attributes and cognitive function were tested by fitting multivariate linear regression models. Each exposure, including residential density, diversity of destinations, access to destinations, transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and neighbors physically active, was separately examined with cognitive function. All models were adjusted for age, sex at birth, race/ethnicity, and education. Coefficients from linear regression model and corresponding 95% confidence intervals (CI) were reported. Sensitivity analysis was conducted in a subsample of people who lived in their home address for at least six years (n = 760). All statistical analyses were conducted with R statistical software version 3.6.2 (R Core Team, 2019).

Results

The characteristics of participants and perceived neighborhoods are presented in Table 1. Respondents were, on average, 76.3 years old (*SD* = 6.3), with a range of 65 to 97. One half of participants were female (n = 440, 53.6%). Most respondents were non-Hispanic White (n = 727, 88.6%) and reported more than 15 years (n = 659, 80.3%) of education. More than 90% of participants lived in the same neighborhood for at least six years (n = 760, 92.6%). Almost two-thirds of participants reported perceiving that they lived in a neighborhood with low residential density. The perceived neighborhood attribute with the highest mean score was transit access (*M*

= 3.7, *SD* = 0.8), and the perceived neighborhood feature with the lowest average score was diversity of destinations (*M* = 2.7, *SD* = 1.2).

The findings on the associations between perceived neighborhood attributes and cognitive function are reported in Table 2. In unadjusted models, greater diversity of destinations, transit access, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and neighbors physically active were associated with greater cognitive function. After controlling for individual-level factors, only transit access and sidewalk coverage remained associated with cognitive function. Individuals living in areas with a one-point higher transit access score had 0.56 points higher cognitive function scores on average (95% confidence interval [CI]: 0.25, 0.88). Individuals living in neighborhoods with one-point higher sidewalk coverage score reported 0.22 points higher cognitive function score on average (95% CI: 0.00, 0.45).

In a sensitivity analysis with a subsample of people who lived in their home address for at least six years, the adjusted association between transit access and cognitive function remained. However, the adjusted association between sidewalk coverage and cognitive function was no longer statistically significant.

Discussion

This cross-sectional study provides preliminary evidence regarding the role of perceived neighborhoods on cognitive function in older adults. Our study found that greater perceived transit access and sidewalk coverage were associated with better cognitive function in older adults. The finding was observed as we hypothesized. Only few studies examined the relationship between perceived built environment and cognitive function in older adults. To our knowledge, no study investigated the association between perceived transit access and cognitive

function as well as perceived sidewalk coverage and cognitive function among older adults. The study finding build on previous literature. A cross-sectional study was conducted in Taiwan among older adults aged 65 years and older (Hsu & Bai, 2021). The authors found that barrier-free sidewalks at city-level was positively correlated with cognitive function (Hsu & Bai, 2021). Perceived presence of sidewalk in a neighborhood was associated with both walking for transportation and leisure among people aged 60 years and above in Brazil (Corseuil Giehl et al., 2017). Physical activity is a well-known protective factor for cognitive health (Zhou et al., 2020). More frequent use of public transportation was related to better cognitive function among people aged 50 years and older residing in England (Reinhard et al., 2019). These connections may explain the associations of perceived transit access and sidewalk coverage with cognitive function in our sample. However, the association between perception to sidewalk coverage and cognitive function was not observed in the sensitivity analysis, probably due to relatively homogenous characteristics of the sub-sample in terms of range of sidewalk coverage scores and cognitive function scores. Further studies are needed to fully understand the relationships between perceived neighborhood and cognitive function.

Our study found that greater perceived land use-mix (diversity of destinations), recreation facilities, safety from crime, safety from traffic, and neighbors physically active were significantly related to better cognitive function, but the significant associations did not remain after including individual-level sociodemographic factors. Unlike our study, other studies found significant associations. A cross-sectional study revealed that greater perceived land use-mix (diversity of destinations) was related to better cognitive function in adults aged 55 years and older residing in Singapore (Ng et al., 2018). Another cross-sectional study observed that greater perceived danger in their neighborhoods was related to worse cognitive function in 2,260 older

adults, with 71.4 mean age, in the United States (Lee & Waite, 2018). In our study, variability in cognitive function was mostly explained by individual factors such as age and education. Our participants were relatively healthy and highly educated. Individual characteristics such as education may work as a buffer against neighborhood stressors, such as crime and traffic, which may adversely affect cognitive function (Richards & Deary, 2005; Stern, 2002). This may be one of the reasons that we did not find significant associations. Moreover, the mean score of cognitive function measured by CASI in our participants was 95.5 with 4.1 standard deviation in possible range from 0 to 100. Additionally, there was little variability in scores of perceived neighborhood attributes in participants. Lack of ranges in exposure and outcome measures could limit the ability to find the associations between them.

The current study had several limitations. First, given the nature of a cross-sectional study, the causal relationship between perceived neighborhood environments and cognitive function cannot be determined. Specifically, it is possible that individuals with cognitive impairment may perceive their neighborhood environments more poorly than individuals without cognitive impairment. Individuals with better cognitive function may choose to live in areas with greater access to public transit and sidewalk coverage. We measured cognitive function by CASI; a score below 86 indicates possible dementia. However, the average cognitive score in our sample was 95.5, and it indicates that almost all participants were cognitively intact. Cognitive impairment is less likely to influence participants' perception of neighborhood environments in our study. Second, our sample was healthy, educated, and predominantly White race as well as living in neighborhoods that had a moderate to upper socioeconomic status. Additionally, many ACT study participants did not complete the perceived neighborhood attribute questionnaire and those who refused to fill out the survey were more likely to have lower cognitive function. Thus,

our study may include the most cognitively healthy people in ACT cohort. These characteristics of the sample may limit external validity. The findings reported in the current study may not be applicable to ethnically diverse populations and as such, future research would benefit from including more ethnically diverse participants.

Conclusion

Our study included diverse perceived neighborhood attributes and examined their associations with cognitive function in older adults. The findings add preliminary knowledge on the role of perceived neighborhood environments on cognitive function in older adults. We found that perceived neighborhood attributes, particularly greater access to public transit and greater sidewalk coverage, are associated with better cognitive function in older adults. Further studies are needed to fully understand the relationships between perceived neighborhood attributes and cognitive function among older adults. Specifically, including individuals with ethnically diverse participants, with varying levels of cognitive function, and sampled from more diverse regions can help to increase the ability to find the significant associations between perceived neighborhoods and cognitive function. Increasing perception of neighborhood features that can promote social interactions and physical activity by modifying physical infrastructure or by providing social or educational interventions may have beneficial impacts on cognitive function in older adults. To develop social and educational programs for increasing the perceived neighborhood features, future research is required to further understand what other factors at the individual- and neighborhood-level may affect the individual perception of physical environments. Moreover, examining potential mediators of the associations between perceived neighborhood attributes and cognitive function can be helpful to illuminate which chain, from neighborhood environments to potential mediators to cognitive function, is effective.

Researchers and policymakers should consider perceived neighborhood attributes alongside physical neighborhood attributes, to improve cognitive function in older adults.

Table 3.1
Characteristics of participants (N = 821)

Characteristics	n (%)
Age group (years)	
65-74	378 (46.0)
75-84	345 (42.0)
≥ 85	98 (11.9)
Sex at birth	
Female	440 (53.6)
Male	381 (46.4)
Race/ethnicity	
Hispanic or non-White	94 (11.4)
Non-Hispanic White	727 (88.6)
Education (years)	
< 12	6 (0.7)
12-15	156 (19.0)
> 15	659 (80.3)
Length of residence (year)	
1-5	61 (7.4)
6-10	246 (30.0)
11-20	387 (47.1)
≥ 21	127 (15.5)
Cognitive Abilities Screening Instrument < 86[a]	20 (2.4)
Cognitive Abilities Screening Instrument, mean (sd)	95.5 (4.1)
Physical Activity Neighborhood Environment Scale	
Residential density	
High	302 (36.8)
Low	519 (63.2)
Land-use mix, diversity, mean (sd)	2.7 (1.2)
Land-use mix, access, mean (sd)	3.1 (1.0)
Transit access, mean (sd)	3.7 (0.8)
Bicycling infrastructure, mean (sd)	3.0 (1.1)
Recreation facilities, mean (sd)	3.3 (0.9)
Sidewalk coverage, mean (sd)	3.3 (1.2)
Crime safety, mean (sd)	3.1 (1.0)
Traffic safety, mean (sd)	3.3 (0.9)
Physically active neighbors, mean (sd)	3.3 (0.9)

[a] Cognitive Abilities Screening Instrument score less than 86 indicates potential presence of dementia

Table 3.2

Association of perceived neighborhood attributes with cognitive function

	Crude model	**Adjusted model**
	Coeff (95% CI)	Coeff (95% CI)
Residential density: high (vs. low)	0.40 (-0.18, 0.97)	0.14 (-0.39, 0.67)
Land-use mix, diversity	0.37 (0.14, 0.60) **	0.13 (-0.09, 0.34)
Land-use mix, access	0.39 (0.12, 0.66)	0.20 (-0.05, 0.45)
Transit access	0.87 (0.54, 1.21) ***	0.56 (0.25, 0.88) ***
Bicycling infrastructure	0.24 (0.00, 0.49)	0.05 (-0.17, .28)
Recreation facilities	0.36 (0.06, 0.65) *	0.03 (-0.26, 0.31)
Sidewalk coverage	0.31 (0.07, 0.55) *	0.22 (0.00, 0.45) *
Crime safety	0.51 (0.22, 0.79) ***	0.26 (-0.03, 0.54)
Traffic safety	0.53 (0.20, 0.85) **	0.24 (-0.07, 0.55)
Physically active neighbors	0.47 (0.15, 0.79) **	0.21 (-0.09, 0.51)

Abbreviation: Coeff, coefficient from linear regression; CI, confidence interval

Crude model included only each perceived neighborhood attribute. Adjusted model included each neighborhood attribute and controlled for age, sex at birth, race/ethnicity, and education.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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Chapter 4. Mediating Role of Walking between Perceived and Objective Walkability and Cognitive Function in Older Adults

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Abstract

Background: The association between walkability and cognitive function among older adults is under-researched. Perceived and objective walkability may be differentially associated with cognitive function. This study examined the association of perceived and objective walkability with cognitive function separately. Walking is a potential mediator to explain the associations. This study examined if walking has an indirect effect on the associations either between perceived walkability and cognitive function or objective walkability and cognitive function.

Methods: The study employed a cross-sectional design analyzing existing data. Data were obtained from the Adult Changes in Thought Activity Monitor study. Cognitive function and perceived walkability were measured by a survey. Objective walkability was measured using geographic information systems (GIS). Walking was measured using an accelerometer. Associations were tested using linear regression. Indirect effects were tested using causal mediation analysis.

Results: Walking had an indirect effect on the association between perceived walkability and cognitive function but not on the association between objective walkability and cognitive function.

Conclusions: Perceived walkability may be more relevant to walking behavior among older adults. Modifying neighborhood infrastructure may not be sufficient to improve perceived walkability. Educational or social support programs are required to improve perceived walkability. The improved perceived walkability may encourage older adults to be more physically active and the benefits of physical activity may improve cognitive function in older adults.

Introduction

Growing evidence suggests that neighborhood environments are linked to various health outcomes, including cardiovascular diseases, type 2 diabetes, stroke, mental health, cancer, obesity, and musculoskeletal conditions (1, 2). However, the potential impacts of neighborhood environments on older adults' cognitive function have been given little attention (3-5), despite the high prevalence of Alzheimer's Disease and Alzheimer's Disease Related Dementias (6.2 million) in the United States (US) as of 2021 (6). The few studies that have investigated this association found that people living in areas with high land-use mix have a lower risk of cognitive impairment (7) and dementia (8). Higher street connectivity (i.e., how well streets are connected) is related to a lower risk of cognitive impairment (9) and better cognitive function (10, 11). A walkability index, developed using a weighted composite score of residential density, street connectivity, and land-use mix, is also associated with better cognitive function (11) and better neuroimaging outcomes (12). Walkability in this entire study refers to a measure of the degree to enticing and supporting walking (13, 14).

Potential mechanisms that establish the association between neighborhood attributes and cognitive function are physical activity, cognitive activity, and social engagement (1, 15). Physical activity is a promising modifiable factor that can improve brain health and preserve cognitive function by reducing cardiovascular risk factors and modifying brain metabolism and structure in older adults (16). Hence, older adults are recommended to engage in at least 150 minutes of moderate-intensity aerobic physical activity per week or to be as physically active as possible (17). Walking is the most popular and convenient physical activity for older adults, because it does not require special skills or equipment, and its intensity can be easily adjusted based on one's physical ability (18, 19). The positive association between walkability and

walking has been observed among older adults (20). Walkability is associated with promoting daily walking, which is in turn linked to better cognitive function. Walking combined with social engagement and cognitive activity might partially explain the connection between walkability and cognitive function in older adults. Understanding its mechanism is critical to identify which pathway interventions should be targeted to improve cognitive health.

Despite the importance of understanding the mechanism, few studies have investigated the indirect effects of walkability on cognitive health through physical activity in older adults (9, 11, 21). However, these studies performed mediation analysis by determining whether a significant association between walkability and cognitive health remained or was attenuated after adjusting for physical activity, rather than by conducting a formal causal mediation analysis. A study performed a mediation analysis of physical activity on the association between walkability and brain imaging using the bootstrap-based product of coefficients test, but the study was conducted only among individuals with mild cognitive impairment or Alzheimer's disease (12). Thus, the result may differ among older adults with normal cognitive function. Moreover, most studies included objective walkability, measured by geographic information system (GIS) or neighborhood audits. A few studies have nonetheless found low to moderate agreement between the objective and subjective measures (e.g., survey) of neighborhood environments (22, 23). Perceived neighborhood attributes are influenced by individual judgment of physical neighborhood environments and may differ from objective measures. Perceived neighborhood attributes may be distinctly related to walking as well as to cognitive function.

The aims of this study were to: 1) examine the association between perceived and objective walkability and cognitive function in older adults, and 2) test if walking mediated the indirect effect on the associations (Figure 1). We hypothesized that having greater perceived

walkability and living in areas with greater objective walkability would be associated with better cognitive function, and that walking mediated the associations partially or fully.

Methods

Design and Participants

This is a cross-sectional study that analyzed existing data collected as part of the Adult Changes in Thought Activity Monitor (ACT-AM) study. Its parent study, the ACT study, is a prospective cohort study that began in 1994 to investigate the incidence of dementia and related risk factors among community-dwelling older adults (24). Adults aged 65 and above without dementia were randomly selected from the King County members of Kaiser Permanente Washington (KPWA). The cohort was expanded in 2000 and continuous enrollments were initiated in 2004 to compensate for dropouts due to development of dementia, loss to follow-up, or death (25, 26). Biennial follow-ups were arranged for the cohort members, during which they underwent an additional diagnostic assessment for dementia if they indicated low cognitive screening scores.

The ACT-AM study was launched in 2016 to better understand the sedentary and physical activity patterns among older adults (27). Those who were wheelchair-bound, had critical illnesses, and resided in nursing homes were excluded from the study. Participants were asked to wear activity monitoring devices (Actigraph wGT3X+ and activPAL micro) and to log their detailed device wear and sleep for seven days. The ACT-AM study only included valid physical activity data (i.e., data for more than 10 hours of out-of-bed time for at least four days). In the present study, participants who resided outside King County were excluded. Data on demographic factors, perceived walkability, and cognitive function were available from the ACT study, collected from 2016 to 2019. A total of 829 participants were eligible for this study. After

excluding missing data on cognitive function (n = 11) and race/ethnicity (n = 4), 814 observations were included in the analysis.

Measures

Outcome: Cognitive function

Cognitive function was measured with the Cognitive Ability Screening Instrument (CASI), consisting of nine domains: attention, concentration, orientation, short-term memory, long-term memory, language abilities, visual construction, list-generating fluency, and abstraction and judgment. Purpose of this study is to determine the association between neighborhood attributes and cognitive function and its mediator to inform developing strategies to prevent and delay cognitive decline and development of dementia. The total score that can be used to identify potential dementia, rather than domain specific scores was selected. The total score ranges from 0 to 100 with a higher score indicating better cognitive function (28). Outcome data were collected once between 2018 and 2019 except for one case measured in 2017.

Exposures: Perceived and objective walkability

Walkability is defined as the degree to enticing and supporting walking in this study (13, 14). Perceived neighborhood walkability was measured using a neighborhood environment index from the Physical Activity Neighborhood Environment Scale (PANES) which was developed based on adult participants (29). In the PANES survey, a home neighborhood is defined as a surrounding area within a 10 to 15-minute walking distance from home. This study included six questions from the PANES questionnaire about residential density, land-use mix, transit access, sidewalk coverage, bicycling infrastructure, and recreation facilities. Residential density was measured by inquiring about the main type of housing in a participant's neighborhood. Detached single-family housing was considered as having low residential density, and other types of

housing such as condos, townhouses, or apartments were regarded as having high residential density. Land-use mix was assessed by checking whether essential service establishments, such as shops, markets, or other places to buy things from, were located within a short walking distance of home. Regarding transit access, participants were asked whether there was a transit stop within walking distance from home. Sidewalk coverage referred to the sidewalk coverage on most streets in the participant's neighborhood, and bicycling infrastructure pertained to existence of facilities supporting bicycling in or near the participant's neighborhood. Recreation facilities were measured by asking whether the neighborhood had several free or low cost recreational facilities, such as parks, trails, and recreation centers. All questions except the one about residential density had four response options ranging from 1 – indicating strongly disagree to 4 – indicating strongly agree. The responses to the six questions were dichotomized (1 and 2 to 0; 3 and 4 to 1). A perceived walkability index was calculated by adding the six dichotomized items (29, 30). The possible range was 0 to 6 with a higher score indicating greater walkability in the neighborhood. The data were collected at one time between 2016 and 2019.

An objective walkability index for each participant's home neighborhood was created using GIS for the spatial data processing. An 800 m Euclidean buffer was created for each central point of the census block (i.e., the smallest geographic unit used to collect decennial census data) where participants resided, rather than at the actual residence locations to protect participant identities. The 800 m buffer corresponded to a 10 to 15-minute walking distance. Because they were based on GIS measurements within the buffer, objective neighborhood walkability index values were identical for individuals living in the same census block. Of the 713 census blocks within the study area, only 75 census blocks (10.5%) had more than two participants.

The objective walkability index was created using a weighted composite score of land-use mix, residential density, and intersection density which has been applied to adult participants (31). There is no limit in possible range for the objective walkability index and a higher score indicates greater walkability. A negative value does not necessarily mean low walkability; the raw value of the index is less informative as the difference in index values from location to location. Land-use mix was developed using the 2016 King County Assessor's data for parcels, with reclassifying predominant use into residential, commercial, office, or none of the three land-use types. Data were processed using an area-based entropy formula that describes the evenness in the distribution of areas with residential, commercial, and office land-uses (31, 32). Residential density was calculated using housing unit counts within a buffer area in square meter (count/m^2) and data were also obtained from 2016 King County Assessor's data. Intersection density was measured using the number of three-way intersections divided by the buffer area in square meter (count/m^2), from 2016 US Census TIGER/Line road data. Data for both residential and intersection density were converted from vector format using the selected buffer size to SmartMaps which is a spatial data format developed for efficient data extraction for area-level variables at any point location within the study area (33).

Mediator: Walking

Walking was quantified as average daily step counts for each participant using a thigh-worn accelerometer (activPAL micro, PAL Technologies, Glasgow, Scotland, UK), a validated device for measuring steps in older adults (34). The detailed methods are published elsewhere (27). Briefly, consenting participants were asked to wear the device for seven days and to keep a log for the times at which they went to sleep at night and got up in the morning; accelerometer data recorded during sleeping bouts were not included in the analyses. All steps were counted

regardless of when (weekends vs. weekdays) and where (home neighborhoods vs. other areas) they were taken.

Other covariates

Other covariates included age (65–74 years, 75–84 years, ≥ 85 years), sex assigned at birth (female, male), race/ethnicity (non-White race or Hispanic ethnicity, non-Hispanic White), education (< 12 years, 12–15 years, > 15 years), self-rated health (excellent, very good, good, fair, poor), and duration of residence (1–5 years, 6–10 years, 11–20 years, and ≥ 21 years). All covariates except the duration of residence were measured from 2016 to 2018 (mostly between 2016 and 2017). The duration of residence was calculated from the history of their address since enrollment in the study.

Statistical Analysis

Descriptive statistics for all individual- and neighborhood-level variables were calculated. We assumed that perceived and objective walkability capture different aspects of actual neighborhood environments. Therefore, for both perceived and objective neighborhood walkability, unadjusted and adjusted linear regression models were fitted between walkability and cognitive function (exposure and outcome), walking and cognitive function (mediator and outcome), and walkability and walking (exposure and mediator) to assess associations among exposures, the mediator, and outcome. In the analysis with perceived walkability as exposure, 680 cases were included due to missing perceived walkability values from the survey (n = 134). Accounting for 15 missing objective values, 799 observations were included in the analysis with objective walkability as an exposure. In all adjusted models, age, education, race/ethnicity, and sex at birth were controlled. For mediation analysis, a model-based approach was applied (35). Two models were developed: a mediator model specifying the conditional distribution of the

mediator, given the exposure and confounders; and an outcome model specifying the conditional distribution of the outcome, given the exposure, mediator, and confounders (36). After these two models were applied, the average causal mediation effects (ACME) representing the population averages of the mediation effect on the association between walkability and cognitive function was estimated (i.e., indirect effect). Subsequently, the bias-corrected and accelerated (BCa) confidence intervals were computed for the ACME estimate based on 1,000 simulations (i.e., bootstrapping). The mediation R package version 4.5.0 was utilized. All statistical analyses were performed using R version 3.6.2 (37) and the GIS analysis was conducted using Esri ArcGIS Pro version 2.4 (38). Processing of vector data to SmartMaps was performed using R 3.6.0 with the sf, raster, and velox packages, and PostgreSQL 11.6 with the PostGIS 2.5 spatial extension.

Results

Table 1 presents the sample descriptive statistics. The mean age was 77 years (SD = 6.7) with slightly more than half the participants being female (n = 470, 57.7%). The majority of participants were non-Hispanic White (n = 724, 88.9%) and highly educated (greater than 15 years, n = 615, 75.6%). Most participants had lived at their home addresses for at least six years (n = 738, 90.7%) and regarded their health either good (n = 252, 31.0%) or very good (n = 351, 43.1%). The mean CASI score was 95.2 (SD = 4.7). On average, the perceived walkability score was 4.17 (SD = 1.49) and the objective walkability score was -0.13 (SD = 7.3) with a range from -11.3 to 23.0. Pearson correlation coefficient for the association between perceived and objective walkability was 0.37.

Table 2 shows the association of both perceived and objective walkability with cognitive function. Higher perceived walkability was linked to better cognitive function ($p < .01$), while objective walkability was not associated with cognitive function. A one-point increase in

perceived walkability was associated with a 0.29 points higher cognitive function score. However, the association between perceived walkability and cognitive function was no longer statistically significant after including the potential confounders (i.e., age, education, race/ethnicity, and sex at birth). Table 3 reports the relationship between walking (steps/day) and cognitive function. Walking (steps/day) was positively associated with cognitive function after adjusting for age, education, race/ethnicity, and sex at birth ($p = .02$). For a daily increase of 1,000 steps, the cognitive function score was higher by 0.1 points after accounting for the confounders. The significant association between walking and cognitive function persisted after separately including each potential mediator (i.e., Model 3 for perceived walkability and Model 4 for objective walkability). Table 4 indicates the positive relationship between perceived walkability and walking after accounting for confounders ($p < .01$). A one-point increase in the perceived walkability score was associated with 338.4 more daily steps after controlling for confounders. Table 5 presents the analysis result of walking as a mediator in the associations between perceived walkability and cognitive function and objective walkability and cognitive function. The estimated ACME, indicating the size of the indirect effect of perceived walkability on the cognitive function through walking was 0.035 ($p = .01$). Walking was a mediator for the association between perceived walkability and cognitive function. However, walking had no indirect effect on the relationship between objective walkability and cognitive function, as it was not a mediator there.

Discussion

The current study adds evidence to suggest the relationship between walkability and cognitive function, and fills the research gap on the mechanism of their association among community-dwelling older adults. Walkability was assessed using both perceived and objective

measures (i.e., a questionnaire and GIS data, respectively) to account for the possible different associations with cognitive function (11).

First, we tested if greater walkability was associated with better cognitive function in older adults. We found a significant association between perceived walkability and cognitive function in the unadjusted model but not in the adjusted model. This might imply that variations in perceived walkability are substantially accounted for by individual characteristics such as age. To the best of our knowledge, a perceived walkability index measured using a survey has not been examined with regard to cognitive function in older adults, but the individual features composing the perceived walkability index have been investigated regarding cognitive function. A cross-sectional study of 402 adults aged 55 years and older was conducted in Singapore (11). The authors found that cognitive function was associated with perceived land-use mix (i.e., the presence of diverse stores and facilities in a neighborhood) but not with residential density and street connectivity (11), measured by the Neighborhood Environment Walkability Scale (NEWS) (39). Future studies should examine perceived neighborhood features seperately and the perceived walkability as an composite index with cognitive function to understand which perceived neighborhood features and how perceived walkability are linked to cognitive function in older adults.

In the current study, objective walkability was not associated with cognitive function. Guo et al. (2019) investigated the association of neighborhood environmental characteristics, including the Walk Score walkability index (objective measure) that was created using weighted distance to nearby frequently visited amenities (40), with cognitive function and dementia in Hong Kong residents aged 65 years or older (41). The authors indicated that the objective walkability index at the census tract level was not associated with cognitive function measured

by the Mini-Mental State Examination (MMSE), but was associated with a lower risk of dementia among older adults (41). On the other hand, Ng et al. (2017) conducted a cross-sectional study in Singapore using a neighborhood definition of a Euclidean 500-meter buffer around the home address (11). The authors found a significant relationship between objective walkability (measured using a combined score of land-use mix, residential density, and street connectivity) and cognitive function in 402 adults aged 55 years and older. The inconsistency in findings may be due to different neighborhood definitions, environmental characteristics, study areas, and characteristics of participants such as age.To understand the effects of objective walkability on cognitive function, further studies are needed.

Second, we examined whether walking (i.e., number of daily steps) mediates the association between both perceived and objectively measured walkability, and cognitive function in older adults. Before performing a formal statistical mediation analysis, we explored associations between walkability and walking, as well as between walking and cognitive function. We found that perceived walkability was associated with walking, which were in turn related to cognitive function, accounting for perceived walkability and potential confounders. This is consistent with previous research. Perceived residential density, street connectivity, and land-use mix were associated with the physical activity of transportation in adults aged 55 years or older living in Singapore (39). Perceived walkability was related to walking time in Chinese adults aged 60 years or older (42). Physical activity is a well-known modifiable factor for cognitive function (16). Unlike with perceived walkability, we did not find a significant association between objective walkability and walking. It is possible that there was little variability in objective walkability in the study region, King County. A study conducted in Atlanta quantified objective walkability using the same formula used in this study reported larger

standard deviation and broader range, 11.3 and -14.7 to 30.5, respectively (31) compared to our study, 7.26 for standard deviation and -11.3 to 23.0 for range. This might limit the ability to find the association. It is also possible that all participants resided in neighborhoods that were relatively supportive of walking. Based on this exploratory analysis, we expected to find indirect effects of walking on the association between perceived walkability and cognitive function, but not on the association between objective walkability and cognitive function.

By convention, mediation analysis is conceptualized such that mediation can be tested in the presence of total effect (i.e., a significant association between exposure and outcome) (43). Recent methodological research recommends assessing an indirect effect regardless of the presence of a significant total effect if there are theoretical reasons to support the existence of an indirect effect (44, 45). Although we could not find a significant association in adjusted models for perceived walkability and cognitive function as well as objective walkability and cognitive function, an indirect effect was analyzed. As expected, we found perceived walkability's indirect effect on cognitive function through walking by a bias-corrected and accelerated confidence interval based on 1000 bootstrap samples. To the best of our knowledge, no other studies have formally tested the indirect effect of daily steps on the association between perceived walkability and cognitive function among older adults.

In contrast to our hypothesis, our study did not detect an indirect effect of objective walkability on cognitive function through walking. A cross-sectional study presented a significant association between objective walkability (using a weighted composite score of residential density, street connectivity, and land-use mix) and cognitive function; the association was slightly attenuated after adding self-reported transportation physical activity and leisure activity among 402 adults aged 55 or above in Singapore (11). A study examined whether self-

reported leisure time and transport-related physical activity was a mediator for the association between objective walkability (using a composite score of residential density, street connectivity, and land-use mix) and brain imaging outcomes (Amyloid β burden, ventricular volume, hippocampal volume, and gray matter volume) among 127 individuals with mild cognitive impairment or Alzheimer's disease (74.9 years old on average) in Australia (12). The authors reported that only a small portion of the cross-sectional associations with no longitudinal associations (18 months follow-up) were explained by self-reported physical activity (12). Our finding is generally inconsistent with previous studies that have shown promising results of physical activity as a mediator for the association between objective walkability and cognitive function. In the current study, objective walkability was not associated with walking. Additionally, all steps were counted, regardless of whether they were taken within the home neighborhood. The walking occurred outside of the home neighborhood may be influenced by other factors but not objective walkability within the home neighborhood, then the association between objective walkability and walking could be attenuated or overestimated. Due to a potential mismatch between home neighborhood environmental characteristics and where walking occurred, we may not find a significant indirect effect of walking on the association between objective walkability and cognitive function. Global positioning system (GPS) measurements in future research could be used to identify locations where walking had occurred.

This study had several limitations. First, because this is a cross-sectional study, causal relationships cannot be drawn. There is a possibility for residual confounding and residential self-selection. The potential bias was not able to fully controlled for due to limited data availability (e.g., cross-sectional data and limited available variables such as a preference to live in high walkable areas). These factors could distort the associations between variables. Further

longitudinal studies are required to establish a temporal sequence among exposure, mediator, and outcome, as well as to control for residential self-selection by examining associations among changes in those variables over time. Second, all steps taken during walking time were counted regardless of location and purpose (i.e., recreational or utilitarian). Walking that occurred outside of a neighborhood could be affected by factors other than the walkability of the home neighborhood. Third, our participants were healthy, highly educated, and predominantly White, and resided in King County, WA. The characteristics of our sample may limit generalizability. Lastly, the perceived and objective walkability measures were not validated among older adults. Adding other built environment features that are associated with older adults' walking or cognitive function to the walkability index can advance the walkability measures.

Conclusions

Our study indicated that perceived walkability can be indirectly associated with cognitive function through walking. This finding can contribute to acquiring a better understanding of the mechanism of the association between walkability and cognitive function in older adults. A better understanding of it would assist in identifying more effective and cost-efficient interventions to improve cognitive function in older adults. Knowing the mechanism could also help researchers and policy makers determine which component should be intervened with and evaluate the intervention's interim effectivness by examining whether the mediator is improved after the intervention is initiated. Our finding implies that older adults who have better perceptions of their neighborhood are more likely to benefit from an intervention modifying infrastructure to increase objective walkability. Modifying neighborhood infrastructure is required but not sufficient to improve cognitive function in older adults. Educational or social support programs to improve perceived walkability are also needed to promote cognitive

function. The effectiveness of the programs can be examined by evaluating physical activity (interim outcome) and cognitive function. This would help understand how programs work to improve cognitive function in older adults. Future studies could test other potential mediators, such as social and cognitive activities, for a deeper understanding of the effectiveness of walkable neighborhoods on cognitive function among older adults.

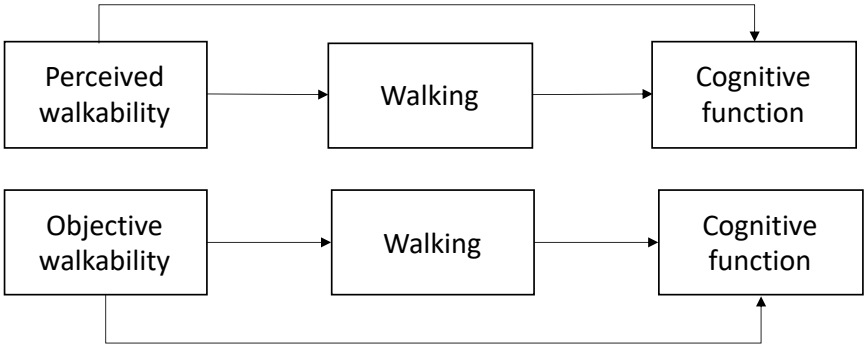

Figure 4.1. Pathways from perceived and objective walkability to cognitive function through walking

Table 4.1. Individual-level and neighborhood-level characteristics (N = 814)

Characteristics	Mean (SD) or n (%)
Individual-level characteristic	
Age group	
65-74 year	343 (42.1)
75-84 year	348 (42.8)
≥ 85 year	123 (15.1)
Sex at birth	
Female	470 (57.7)
Male	344 (42.3)
Race/ethnicity	
Hispanic or non-White	90 (11.1)
Non-Hispanic White	724 (88.9)
Education	
< 12 year	12 (1.5)
12-15 year	187 (23.0)
> 15 year	615 (75.6)
Self-rated health	
Poor	8 (1.0)
Fair	41 (5.0)
Good	252 (31.0)
Very good	351 (43.1)
Excellent	162 (19.9)
Duration of residence	
1-5 year	76 (9.3)
6-10 year	128 (15.7)
11-20 year	244 (30.0)
≥ 21 year	366 (45.0)
Cognitive function (possible range 0-100)	95.19 (4.73)
Neighborhood-level characteristic	
Perceived walkability (possible range 0-6)	4.17 (1.49)
Objective walkability (possible range: no limit)[a]	-0.13 (7.26)

A higher cognitive function, perceived walkability, and objective walkability scores indicate better cognitive function, greater perceived walkability, and greater objective walkability, respectively.

[a] The range of the objective walkability score in our data was -11.3 to 23.0.

Table 4.2. Association of perceived and objective walkability with cognitive function

	Perceived walkability (n = 680)		**Objective walkability (n = 799)**	
	Coeff (95% CI)	*P* value	Coeff (95% CI)	*P* value
Model 1	**0.290 (0.084, 0.496)**	**0.006**	-0.003 (-0.048, 0.042)	0.896
Model 2	0.143 (-0.051, 0.337)	0.149	-0.003 (-0.044. 0.038)	0.888

Coeff, coefficient from linear regression model; CI, confidence interval

Model 1: perceived and objective walkability and cognitive function only

Model 2: model 1 plus age, education, race/ethnicity, and sex at birth

Table 4.3. Association between walking and cognitive function (N = 814)

	Coeff (95% CI)	***P* value**
Model 1	**0.0003 (0.0002, 0.0004)**	**< 0.001**
Model 2	**0.0001 (0.0000, 0.0002)**	**0.015**
Model 3	**0.0001 (0.0000, 0.0002)**	**0.019**
Model 4	**0.0001 (0.0000, 0.0002)**	**0.015**

Coeff, coefficient from linear regression model; CI, confidence interval

Model 1: averaged number of steps per day and cognitive function only

Model 2: model 1 plus age, education, race/ethnicity, and sex at birth

Model 3: model 2 plus perceived walkability (n = 680)

Model 4: model 2 plus objective walkability (n = 799)

Table 4.4. Association of perceived and objective walkability with walking

	Perceived walkability (n = 680)		**Objective walkability (n = 799)**	
	Coeff (95% CI)	*P* value	Coeff (95% CI)	*P* value
Model 1	**426.2 (256.4, 596.1)**	**<0.001**	11.6 (-21.3, 44.5)	0.489
Model 2	**338.4 (174.7, 502.0)**	**<0.001**	14.9 (-16.1, 45.9)	0.347

Coeff, coefficient from linear regression model; CI, confidence interval

Model 1: perceived and objective walkability and averaged number of steps per day only

Model 2: model 1 plus age, education, race/ethnicity, and sex at birth

Table 4.5. Average mediation effects of walking between perceived and objective walkability and cognitive function

	Perceived walkability (n = 680)		Objective walkability (n = 799)	
	ACME (95% CI)	*P* value	ACME (95% CI)	*P* value
Average daily steps (count/day)	**0.035 (0.010, 0.070)**	**0.006**	0.002 (-0.001, 0.010)	0.300

ACME, average causal mediation effects indicating the size of mediation effects

Adjusted for age, education, race/ethnicity, and sex at birth

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Chapter 5. Conclusions

The Public Health Nursing Section Council of the American Public Health Association, defines public health nursing as "the practice of promoting and protecting the health of populations using knowledge from nursing, social, and public health sciences" (American Public Health Association, 2013). Health of populations is affected by not only individual factors (e.g., genetics, lifestyle) but also social and environmental factors (e.g., neighborhood, social context). From a holistic view, nurses should address social determinants of health, "the conditions in which people are born, grow, work, live, and age, and the wider set of forces and systems shaping the conditions of daily life" (World Health Organization, n.d.), to promote the health of communities and populations. One of the categories of social determinants of health is the neighborhood and physical environment. This study was built on a foundational role of nurses, reducing the unfair burden of illness due to social inequities and structural discrimination. This dissertation adds scientific knowledge and recommends health policies for improving the cognitive health of the older adult population by modifying perceived and physical neighborhood environments. In this chapter, I will summarize key findings from the three studies in this dissertation and discuss their implications and limitations. I will close with recommendations for future studies.

The first study examined the associations between objective neighborhood features and change in cognitive function in a sample of 1,302 adults age 65 and older residing in King County, Washington State. The objective neighborhood features included land-use mix, residential density, intersection density, presence of trails, sidewalk coverage, a gradient of walkways, and park area within 400 m, 800 m, 1,600 m buffers. A difference in cognitive function scores two years apart was used. This study indicated that individuals living in a neighborhood with greater park areas had better cognitive function. A significant association was

observed in only 800 m buffers but not 400 m and 1,600 m buffers. The significant association in 800m buffers was only marginally significant and the effect size was small.

The second study evaluated the associations between perceived neighborhood features and cognitive function in 821 older adults. Perceived neighborhood attributes contained residential density, land use-mix (diversity to destinations and access to destination), transit access, bicycling infrastructure, recreation facilities, sidewalk coverage, safety from crime, safety from traffic, and physicall active neighbors. This study observed that individuals who perceived their neighborhood with greater transit access and presence of sidewalk had better cognitive function in older adults.

The third study investigated if walking mediates the associations between objective walkability and cognitive function in 799 older adults as well as perceived walkability and cognitive function in 680 older adults. Walking was measured using an accelerometer. Objective walkability was captured using a composite score of land-use mix, residential density, and intersection density. Perceived walkability reflected a summed score of residential density, land-use mix, transit access, sidewalk coverage, bicycling infrastructure, and recreation facilities. This study found that perceived walkability had an indirect effect on cognitive function through walking (steps per day).

This series of studies contribute to understanding the role of neighborhoods in improving cognitive health and its mechanism in older adults. The studies note that both objective and perceived neighborhood environments are associated with cognitive function in older adults. The first study explored various sizes of buffers around the location of residence and the significant association between objective neighborhood attributes and cognitive function was observed in only 800 m buffer. The finding provides a preliminary evidence what size of buffer to measure a

home neighborhood is appropriate for older adults, but the optimal size of buffer is still inconclusive.The second study also showed that individual characteristics might work as a buffer against harm from neighborhoods or a barrier to receiving benefits from neighborhoods through modifying the individual perception of their physical neighborhood environments. The third study found a significant indirect effect of walking on the association between perceived walkability and cognitive function, while the study did not find a significant indirect effect of walking on the association between an objective walkability and cognitive function. These studies provide preliminary evidence to policymakers, urban design planners, and researchers for developing and implementing structural and supportive educaitonal interventions to promote older adults' cognitive function. Physical environment is required to promote healthy behaviors and cognitive function but not sufficient. People who have better perceptions to their neighborhood are more likely to benefit from infrastructure improvement. Structural interventions should address physical environments, perceived environments, and other individual factors related to the perception of physical environments. A program improving perceived neighborhoods may include community events of touring a neighborhood, taking photos of a neighborhood, and sharing opinions about a neighborhood. Walking may be used as an interim evaluation for interventions.

The studies have several limitations. First, for the first study, the follow-up period was relatively short to observe substantial cognitive function changes. Second, residential self-selection bias potentially exists. The association between neighborhood environments and cognitive function can be due to the effects of neighborhoods on cognitive function, the effects of personal characteristics related to neighborhood selection, or both. Third, for the second and third papers, given the nature of cross-sectional study, the causal relationship cannot be

determined. Fourth, any home-centered neighborhood buffers may not accurately represent the activity space where older adults actually spend their time and accumulate exposure to environmental features. If the definition of neighborhoods is invalid, neighborhood features measured within a buffer can be overestimated or underestimated and the association can be distorted. Lastly, the sample for the second and third papers was healthy, educated, and predominantly White adults who lived in neighborhoods that were moderate to upper socioeconomic status. Additionaly, there was a little variability in cognitive function scores and neighborhood attributes scores in our data. These characteristics of the sample may limit external validity and ability to find true associations.

Future studies are recommended to follow up cognitive function for a longer period of time. Longitudinal studies examining associations between changes in exposures and changes in outcome may help to reduce residential self-selection bias. Additionally, studies could compare various buffer shapes (e.g., network-based or global positioning system data-based) and sizes to understand the definition of neighborhoods for older adults. Moreover, studies need to include people with diverse backgrounds and those from geographical areas with varying levels of neighborhood attributes. Lastly, other potential mediators for the associations between neighborhood environments and cognitive function should be tested such as social interactions.

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